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Sgr A* 和低光度活动星系核的多波段辐射研究

Multi-wavelength Emissions for Sgr A* and Low-Luminosity Active Galactic Nuclei

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摘　要

黑洞吸积一直是高能天体物理的一个重要过程。本文主要讨论了Sagittarius A* (Sgr A*) 的宁静态和耀发态，以及低光度活动星系核系统的多波段辐射，寄希望于对Sgr A* 的吸积和抛射过程，以及低光度活动星系核的中心引擎有一个统一深入的理解。本文可以主要分为以下四个部分：

在第二章，我们利用现有的法拉第旋转量（RM）观测讨论了Sgr A* 的喷流模型。在过去二十多年里，已经有多个理论模型被用来解释Sgr A* 的宁静态辐射。辐射低效吸积流和喷流模型是其中的两个竞争模型。利用对Sgr A* 在亚毫米波段RM的精确测量，我们寄希望于解除理论模型的简并性。我们发现喷流模型期望的RM比观测值要低两个量级。考虑额外的来自于视线路径上前景吸积流的贡献，模型值可以在一些严格的限制下和观测值吻合。主要的限制是喷流的倾角要满足$\gtrsim 73^\circ$。但是这样的一个限制和已有的通过恒星盘面角动量方向得到的倾角不一致。

在第三章，我们利用*Chandra* 3兆秒的XVP的数据对Sgr A* 的X-射线耀斑做了一个统计分析，并试图探讨耀发背后的物理机制。我们通过蒙特卡洛模拟生成模型光变曲线，然后通过马尔科夫链蒙特卡洛方法，对比观测和模拟光变曲线的计数率分布和结构函数，以此来限制光变曲线中耀斑各种物理量的分布。我们发现$2-8$ keV的X-射线光变曲线可以分解为两个成分，一个为稳定光度的宁静态，其对应的光子计数率为6×10^{-3} count s^{-1}；另一个为幂率分布的耀发成分。耀斑总光子数的幂率分布指数为$\alpha_{\rm E}=1.65\pm0.17$（$dN/dE\propto E^{-\alpha_{\rm E}}$），持续时间-总光子数的相关幂率指数为$\alpha_{\rm ET}<0.55$（$T\propto E^{\alpha_{\rm ET}}$；95% 置信度）。这些统计性质很好地符合三维自组织临界的理论预言。类比于太阳耀斑，我们认为Sgr A* 的X-射线耀发是吸积流中发生的磁重联驱动的等离子团块的辐射表现。

在第四章，我们提出了一个磁流体动力学模型解释Sgr A* 的多波段耀发。Sgr A* 耀发虽然已有大量的观测和理论进展，但其耀发的本质仍然不清楚。基于第三章中的统计工作，类比于太阳日冕物质抛射，我们提出了一个耀斑的理论模型。在此模型中，吸积流中的剪切和湍动会不断扭曲冕区磁力线，使得冕区磁能不断聚集。当聚集到一定程度后，灾变行为发生。这个动力学灾变过程会伴随着之前储存的磁能的大量快速释放，其中一部分转化为我们观测到的耀发辐射。我们首先计算了这个系统的动力学演化过程，然后聚焦于这个动力学过程的辐射表现。考虑了由磁重联导致的电子注入，绝热膨胀以及同步辐射的冷却过程后，我们计算了系统的同步辐射。对比了典型的Sgr A* 耀发观测，我们的模型可以很好的符合耀发的时变、能谱等多方面的性质。我们进一步讨论了多波段耀发的其他性质。

在第五章中，我们研究了两个低光度活动星系核，M87和3C 84，的吸积模型。现在普遍认为低光度活动星系核的中心引擎为耦合的吸积-喷流模型，即内区的径移主导吸积流（ADAF），外区截断的标准薄盘和垂向的准直喷流。但是，单独的喷流或是单独的吸积流往往也可以解释多波段数据。模型的简并问题很难解决。求助于法拉第偏振观测给出的RM测量，我们有希望解决这个问题。M87和3C 84最近有较好的（亚）毫米波段的RM测量。我们基于耦合的吸积-喷流模型给出的能谱拟合结果，计算了M87和3C 84的RM值。由M87偏振观测给出的RM上限，我们可以排除X-射线的ADAF起源。对于X-射线的喷流起源模型，我们的吸积-喷流模型可以符合RM的观测上限。基于能谱拟合和RM观测的结果，我们发现（亚）毫米辐射更有可能起源于ADAF内区，但是亚毫米的喷流起源不能完全被排除。未来更精确的RM测量可以帮助我们更好理解这个问题。对于3C 84，我们发现（亚）毫米辐射由喷流成分主导，而法拉第屏由ADAF外区的等离子贡献。这个图景和3C 84的能谱，时变和偏振观测都符合较好。我们可以进一步约束视线的倾角为$45° \leq \theta \leq 57°$。

在最后一章，我们对接下来的工作做了进一步的展望。

关键词：黑洞；吸积盘；银心；活动星系核

Abstract

Black hole accretion and ejection are crucial processes in high energy astrophysics. In this dissertation, I mainly study the multi-wavelength quiescent and flare emissions from Sagittarius A* (Sgr A*), and multi-wavelength emissions for low-luminosity active galactic nuclei (LLAGNs). The goal of the dissertation is to reveal the accretion and ejection process of Sgr A* and to understand the central engine of low-luminosity active galactic nuclei. The scope of the dissertation is as follows.

In Section 2, we explore the jet model of Sgr A* with the current Faraday rotation measure (RM) observations. There are several theoretical models responsible for the steady state emission of Sgr A* in the past decades. The radiatively-inefficient accretion flow and the jet model are two competitive of them. With the unambiguous detection of the Faraday RM at submillimeter wavelength, we aim to break the model degeneracies. Here we find that the expected RM from the jet model is two orders of magnitude lower than the measured value. With an additional contribution from the foreground accretion flow in front of the jet, the measured RM may be reconciled with the model under a tight constraint that the inclination angle should be $\gtrsim 73^\circ$. But this requirement is inconsistent with the estimated inclination angle inferred from the stellar disk orientation.

In Section 3, we study the statistical properties of the X-ray flares from the 3 million second *Chandra* observations accumulated in the Sgr A* X-ray Visionary Project. We first construct the theoretical light curves through Monte Carlo simulations, and then jointly fit the count rate (CR) distribution and the structure function (SF) of the light curve with a Markov Chain Monte Carlo (MCMC) method. We find that $2-8$ keV X-ray light curve can be decomposed into a quiescent component with a constant count rate of 6×10^{-3} count s^{-1} and a flare component with power-law distributions for various physical quantities. The fluence distribution and duration-fluence correlation can be both modelled as power-law forms with indexes of $\alpha_{\rm E} = 1.65\pm0.17$ ($dN/dE \propto E^{-\alpha_{\rm E}}$) and $\alpha_{\rm ET} < 0.55$ ($T \propto E^{\alpha_{\rm ET}}$; 95% confidence), respectively. These statistical properties are consistent with the theoretical prediction of the self-organized criticality (SOC) theory with the spatial dimension $S = 3$. By analogy with solar flares, we suggest that the X-ray flares of Sgr A* represent plasmoid ejections driven by magnetic reconnection in the accretion flow onto the black hole.

In Section 4, we propose an MHD model for multi-wavelength flares of Sgr A*. Flares from Sgr A* are routinely observed over decades. Despite numerous theoretical efforts on the flare production, the nature of the flare is still poor understood. Motivated by the statistical results in Section 3, we develop an MHD model for flares of Sgr A* by analogy with the coronal mass ejection events on the Sun. In this model, shear and turbulence of the accretion flow deform the magnetic field line and result

in a slow accumulation of magnetic energy in the corona field. When a threshold is reached, further perturbations can lead to catastrophic evolution of the flux rope. The dynamical process is associated with the rapid release of magnetic energy by magnetic reconnection in the current sheet accumulated from the accretion flow, some of which is converted into thermal energy that powers the radiative flares. We first elaborate how the system evolves dynamically and then focus on the emission associated with the dynamical process. After considering the cooling the injection by reconnection cooling by synchrotron and adiabatic expansion process, we obtain the resultant synchrotron emission in the dynamical evolution. Taking a typical simultaneous flare observations for example, our numerical results are well consistent with the observed timing and spectral properties. We further discuss other various aspects of flare properties in multi-wavelength within the context of our model.

In Section 5, we study the accretion model for two LLAGNs. LLAGNs are generally believed to be powered by an inner advection-dominated accretion flow (ADAF), an outer truncated standard thin disk, and a vertical collimated jet (namely accretion−jet model). However, the model degeneracy is a conspicuous problem. With resort to the Faraday RM observations, we hope to resolve this problem. We calculate the RM based on the accretion−jet model for two LLAGNs, M87 and 3C 84, for which the RM in the sub-millimeter (sub-mm) band have been recently detected. With the upper limit of the RM for M87, the ADAF origin of its X-ray emission can be ruled out. By adopting a jet origin for the X-ray emission, our accretion−jet model can be reconciled with the RM upper limit. We further suggest that the sub-mm emission likely originate from the inner region of the accretion flow based on the broad-band spectral modeling and RM observations, although the possibility of the jet origin cannot be ruled out from the RM measurement alone. The future robust detection of the RM in the sub-mm band will help us figure it out. For 3C 84, we find that the sub-mm emission is dominated by the jet component, while the Faraday screen is attributed to the outer region of the ADAFs. This scenario is in well agreement with the spectral, temporal and polarization observations for 3C 84. We can further constrain the viewing angle of the jet to be $45° \leq \theta \leq 57°$.

Key Words: black hole; accretion disk; Sgr A*; active galactic nuclei

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